

Economic benefits of management reform in the eastern Gulf of Mexico reef fish fishery

Quinn Weninger*

February 18, 2004

Abstract

A two step empirical model is used to estimate harvesting efficiency and capacity utilization in the eastern Gulf of Mexico reef fish fishery. The first step exploits advantages of nonparametric frontier analysis. The second step exploits strengths of stochastic frontier analysis controlling for data errors and randomness in harvesting possibly due to adverse weather or good and bad luck. The model is used to study anticipated effects of replacing command and control regulations with a property rights-based program. Results suggest significant fleet downsizing and cost savings, estimated at \$5.518 million (1993 dollars), will emerge under a rights-based management program for reef fish.

Key Words: Rights-based management, harvest efficiency, capacity utilization. *JEL*

Classification: Q2, D2

*Funding from the National Marine Fisheries Service is greatly appreciated. Send correspondence to the Department of Economics, 260 Heady Hall, Iowa State University, Ames, IA, 50011-1070, or email weninger@iastate.edu.

1 Introduction

The eastern Gulf of Mexico commercial reef fish fishery currently operates under command and control regulations wherein the aggregate catch is controlled with minimum size limits for reef fish, restricted harvest season lengths, and limits the location of fishing for some gear types. The management program has failed to achieve biological and economic objectives. The National Marine Fisheries Service classifies several of the reef fish complex's highest-valued and largest volume species as overfished, including red, and yellowedge groupers, and red and vermilion snappers. Regulations designed to protect reef fish stocks raise harvesting costs and have failed to prevent capital build up and fleet harvesting capacity. And, conflict between gear types—vertical hook and line, long lines and fish traps—over increasingly diminished resource stocks subsumes time and effort of regulators charged with protecting reef fish stocks, and industry who lobby to protect their interests.

An individual fishing quota program is currently being considered by regulators and industry as an alternative to controlled access. Individual fishing quotas grant their owner a right to harvest a specified quantity of reef fish. Individual fishing quotas promise to increase economic performance by replacing input controls with market-based incentives to maximize the value of harvested fish. Understandably, regulators and industry are concerned about the short- and longer-term effects of such a dramatic change in management philosophy. The objective of this paper is to predict, *ex ante*, the changes in fleet structure, harvest efficiency, resource rents and quota prices that can be expected in the eastern Gulf of Mexico reef fish fishery if rights-based management is adopted.¹

The changes that are expected are driven by the economic incentives implicit in property rights-based programs. Individual fishing quotas provide incentives to exploit available economies of scale and scope in harvesting, and thus provide a mechanism to align fleet harvesting capacity with sustainable catch levels. Analyzing differences in harvesting effi-

¹Weninger and Waters (2003) study the potential effects of adopting rights-based management in the northern region of the reef fish fishery. Dupont (2000), Squires and Kirkley (1995, 1996), and Squires, Alauddin and Kirkley (1994) provide *ex ante* estimates of the potential gains from tradable harvest permits. Studies examining the performance of existing programs are increasingly available, e.g., Grafton, Squires and Fox (2000).

ciency across existing vessels, and measuring harvest capacity of the existing reef fish fleet provides valuable insights into the redistribution of the catch and fleet downsizing that can be expected in a switch to rights-based management.

A two-step empirical approach is used to study efficiency, and harvest capacity for a sample of eastern Gulf reef fish vessels.² The first step exploits the advantages of nonparametric frontier analysis. The second step exploits strengths of stochastic frontier models controlling for the effects of data errors and randomness in harvesting possibly due to adverse weather, mechanical breakdowns or good and bad luck in locating reef fish. The results find that larger, appropriately powered vessels outperform smaller, and/or over-powered boats. Experienced vessel captains are more productive than less experienced captains, and longline gear outperforms vertical line and fish trap gear. Furthermore, significant excess harvesting capacity is found in the 1993 sample.

These findings suggest that a switch from command and control will result in a redistribution of the catch to larger appropriately powered longline vessels operated by experienced captains. The analysis finds that in the year of the data, 1993, these adjustments could have reduced fleet harvest costs by \$5.518 million (all values are in 1993 dollars), which represents a 30.3% cost saving. Overall, the findings suggest that individual fishing quotas are an attractive alternative to current command and control program.

The next section discusses industry background, and briefly reviews related studies of harvest technology, efficiency and capacity utilization in commercial fisheries. To motivate the empirical specification that follows, section 2 provides a discussion of two empirical issues that arise in commercial fisheries analysis. The first is the choice of data period, i.e., trip-level versus seasonal level analysis, and the second is the measurement and treatment of vessel capital. Section 3 presents a model of a harvest technology, and identifies the efficiency and capacity utilization measures used in the analysis. Section 4 describes the data and the two-step empirical approach, and presents results. A summary of the key findings and concluding remarks appear in section 5.

²The methodology is patterned after Gsatch, (1998), and Fried et. al (2002).

2 Background

The reef fish fishery in the Gulf of Mexico is a complex of bottom-dwelling species consisting of red, black, yellowedge, gag, warsaw and other species of groupers, amberjacks, triggerfish, porgies, tilefish, red, vermillion, and other snapper species, and a host of others. Reef are located throughout the Gulf of Mexico. The region of the fishery studied in this paper extends from Panama City, Florida east and south along the Florida coast to the Florida Keys.

Regulations used to control fishing pressure include vessel licenses, and minimum size restrictions on most species of shallow water groupers. Areas that vessels fishing that fish with long line gear are restricted. More recently, total allowable catch policies that are enforced with seasonal closures have been adopted. Total allowable catches are set at 9.8 million pounds for shallow water groupers and 1.6 million pounds for deep water groupers. Regulators and industry are now examining individual fishing quotas as an alternative to the current management system.

Analysis of harvesting efficiency and capacity in commercial fisheries

Empirical studies of harvest efficiency and capacity utilization in fisheries have employed either stochastic frontier methods, or data envelopment analysis (see Kirkley, Morrison Paul, and Squires, 2002 for a review), or both (Felthoven, 2003). The stochastic frontier methodology estimates a parametric frontier, e.g., a harvest production frontier or cost frontier, and compares observed firm or vessel activity levels (inputs and outputs, or costs) to the estimated frontier. The model specifies a composed error structure consisting of an asymmetric inefficiency component and a symmetric noise term. Estimation of the parametric frontier is carried out using maximum likelihood.³ The presence of noise in the model is an appealing feature which in principle can control for the effects of data errors or randomness in production, due for example, to adverse weather, mechanical breakdowns,

³A comprehensive treatment of stochastic frontier analysis is available in Kumbhakar and Lovell (2000). Applications of the stochastic frontier method to fisheries appear in Kirkley, Squires, and Strand (1995) or Grafton, Squires and Fox (2000).

or good and bad luck.⁴

Data envelopment analysis constructs a piece-wise linear frontier of observed data using linear programming techniques. The nonparametric approach is well-suited for analysis of multiple output technologies. Until recently, however, techniques to explicitly incorporate randomness in data envelopment analyses were unavailable. Applications of data envelopment analysis in commercial fisheries typically assumes a deterministic transformation relationship between inputs and harvested output (e.g., Dupont et. al, 2002; Felthoven, 2003).

Recent work combines the attractive features of the stochastic frontier and nonparametric approaches (see Grosskopf, 1996; Gstach, 1998; and Fried et. al, 2002). The technique is to first estimate firm-level efficiency scores using data envelopment analysis, and then in a second step, estimate a parametric stochastic frontier. Two important advantages for analysis of commercial fisheries arise. First, there is no need to specify and estimate the parameters of harvest (or cost) function, and second the effects of data errors and importantly random production shocks are explicitly incorporated into the model. The two-stage approach will be used in this study.

To motivate the empirical specification that follows, I will discuss briefly the issue of data period and measurement and treatment of capital inputs.

Data period

The focus of an analysis is the harvest technology, efficiency and capacity utilization, and in particular, the transformation relationship between costly inputs and saleable outputs. Much of the empirical work in the fisheries literature studies this transformation relation at the trip-level, although seasonal level analyses are also common. An important question for researchers is, does trip level data provide an accurate representation of the input-output

⁴While often downplayed, endogeneity can pose serious problems in applications of the stochastic frontier methodology. For example, a primal model the harvest frontier must be estimated under the tenuous assumption that input choices are uncorrected with the composed error term. This assumption is even less palatable in applications to multiple output technologies, where estimation of distance or transformation functions must assumed inputs and outputs are uncorrelated with composed error. If regressors are endogenous, maximum likelihood yields inconsistent estimates of the harvest frontier and unreliable measures of efficiency and capacity utilization.

transformation relationship that is relevant for the question being asked? The answer is probably not if, as is the case in most fisheries, fishermen spend time and effort searching for fish, and randomness is an important component of the harvesting process.⁵ A simple example demonstrates this point.

Consider a fisherman who employs a single input, call it *effort*, to harvest a single output, the catch. The fisherman takes two fishing trips. The fisherman must choose a fishing site, but has imperfect information about the true stock abundance at available sites. The fisherman learns about true abundance at a site by fishing it. That is, information about a site's true stock abundance is obtained as fishing proceeds. Suppose the catch at the site that is chosen first falls short of expectations. Based on this low catch per unit effort on the first trip, the fisherman wisely selects an alternate site on the second trip.

The data generated by the simple example might exhibit a low catch per unit of effort on the first trip and a higher catch per unit of effort on the second trip. What is important is that a component of the *output* from the first trip is information about the location of fish. Likewise, a component of the output from the second trip results from an investment in information made on the first trip. The input/output transformation relation embedded in the first (second) trips data provides a downward (upward) biased estimate of a *sustainable* input/output transformation relationship.

A complete treatment of searching effort and information acquisition in a harvest technology is beyond the scope of this study (see Marcoul and Weninger, 2003). The analysis to follow will analyze seasonal data that is aggregated across multiple trips. In principle, seasonal data will provide a more robust picture of the sustainable harvest technology, and thus more accurate predictions of expected changes under property rights-based management.

Capital inputs

The services provided by a vessel, engine, electronic equipment and other capital inputs impact the transformation relation between variable inputs, such as fuel and labor services

⁵ Although often ignored in theoretical models, the location of fish stocks vary randomly across time and space. Marcoul and Weninger (2003) find that a large component of the total fishing effort applied by Mid-Atlantic clam fishermen is spent searching for clams. Smith (2000) surveys a now large literature on search and site selection in commercial fisheries.

of the captain and crew, and the harvested output. Accurate measures of capital service flows are unavailable and most studies use a proxy such as vessel size, or water displacement of the vessel, to proxy for the capital services that are employed. Following this approach, this study assumes vessel length and engine horse power provide a reasonable proxy for vessel capital services.

A capital input such as a fishing vessel is costly to adjust, and lumpy. That is, it is difficult (costly) to increase the flow of capital services that are provided vessel of fixed size, and fisherman cannot employ a fraction of available vessel capital services, i.e., a captain cannot choose to fish with half a boat. The implication for modeling a harvest technology is that capital services may not be freely disposable, and thus monotonicity in the vessel capital input should not be adopted as a maintained hypothesis.⁶ This study assumes that the harvest technology is *locally* monotonic in vessel capital inputs. The assumption is implemented empirically by estimating a different feasible technology set for vessels that vary too much in length (further details are provided below).

In addition to physical capital, human capital and the stock of fish may be important determinants of input/output transformation. In this study, the experience of the vessel captain is used as a measure of human capital endowed to the captain and crew. Regional effects are used to control for unobserved stock abundance.

3 Model

Consider a representative vessel that allocates inputs $x \in \mathbb{R}_+^N$ to produce outputs $y \in \mathbb{R}_+^M$ during a single fishing season. The production set identifies feasible input-output combinations;

$$(1) \quad T(z) = \{(x, y) \mid x \text{ can produce } y \text{ given } z\},$$

⁶Weninger and Strand (2003) find evidence of non-monotonicity in vessel capital for surf clam and ocean quahog fishermen.

where $z \in \mathbb{R}_+^L$, denotes a vector of exogenous environmental, or quasi-fixed factors that condition the set of inputs and outputs. Elements of z may include the capital endowment of the vessel which can be assumed fixed in the short run, stock abundance and regulations used to control overfishing. The technology set $T(z)$ is assumed closed, and convex. Free input disposability is assumed. Output disposability is discussed in the empirical section.

The output directional distance function (ODDF) is a functional representation of the feasible set;

$$(2) \quad \vec{D}(x, y; g_y) = \max\{\beta \in \mathbb{R} | (x, y + \beta g_y) \in T(z)\},$$

where $g_y \in \mathbb{R}_+^M$ ($g_y \neq 0_M$) is a directional vector. The ODDF gives the maximal translation of the output y in the reference direction g_y that keeps the translated output in the set $T(z)$.⁷ The ODDF provides a convenient measure of output-oriented technical efficiency. When $\vec{D}(x, y|g_y) = 0$, no feasible translation of the output vector y is possible, whereas $\vec{D}(x, y|g_y) > 0$ indicates that y is located in the interior of $T(z)$. Frontier output is obtained directly as $y + \vec{D}(x, y|g_y)g_y$. Chambers, Chung, and Färe (1996) and Färe and Grosskopf (2000) provide additional discussion of directional distance functions.

The frequently used Shephard (1970) output distance functions is a special case of the ODDF. At directional vector $g_y = y$, it can be shown that $\vec{D}(x, y|y) = (1 - D_o(x, y))^{-1}$, where

$$(3) \quad D_o(x, y) = \inf\{\delta : (x, y/\delta) \in T(z)\},$$

denotes the Shephard output distance function.

Maximum harvest profits are given by

$$(4) \quad \pi(p, w) = \max_{(x, y) \geq 0} \left\{ py + p\vec{D}(x, y|g_y)g_y - wx \right\},$$

⁷The output directional distance function is conditional on z since it is defined over the set $T(z)$. This dependence is suppressed for notational convenience.

where p , and w denote respectively, prices of outputs and inputs (Färe and Grosskopf, 2000). If z contains capital inputs that are fixed in the short run, the solution to (4) is the short run profit maximizing input, denoted $x^*(p, w|z)$, and short run profit maximizing output, denoted $y^*(p, w|z)$.

Measures of short run input utilization and short run capacity output are obtained by comparing $x^*(p, w|z)$ and $y^*(p, w|z)$ with the actual inputs and outputs employed by a fisherman (see Kirkley, Morrison Paul and Squires, 2002). For example, if a fisherman with capital endowment z employs input $x < x^*(p, w|z)$ to harvest $y < y^*(p, w|z)$ the productive capacity of capital embedded in z is underutilized. Capacity is overutilized in the reverse case.

The next section describes the data and presents the two-stage empirical approach to estimate the ODDF, technical efficiency, and short run capacity utilization in the eastern Gulf reef fish fishery.

4 Data, empirical estimation, and results

Data are from an extensive cost survey that was conducted for the 1993 harvest season (see Waters, 1996 for a detailed description of the data and survey design), and National Marine Fisheries Service log book data. The cost survey elicited information through personal interviews from 196 vessel operators, of which 150 harvested reef fish in the eastern Gulf region. National Marine Fisheries Service Log Book reporting system records trip-level information on harvest quantities, trip length, and the number of crew members on board the vessel.

Sample vessels harvested 4.417 million pounds of fish in 1993 consisting of over 90 different species. While the number of species is large, a much smaller group of species make up the bulk of the catch. Red grouper represents the largest component accounting for 43.4% of the total, vermilion snapper accounts for 13.0%, black grouper (7.3%), sharks (4.9%), grunts (4.8%), gag grouper (4.5%), greater amberjack (2.9%) and yellowedge grouper (2.8%) are also important.

Harvested species are aggregated into three output groups, based on similarity in harvest location and capture methods.⁸ The first output group, y_1 , is made up primarily of shallow water groupers including red, gag, black, yellowfin and yellowmouth grouper. Scamp, red and rock hind, and shark species are also included in y_1 .⁹ The second output category, y_2 , consists primarily of deep water groupers including yellowedge, misty and warsaw groupers, plus speckled hind, golden, blueline and other tilefishes. The third output category consists of all non-reef fish such as king mackerel, yellowfin tuna, bonito, and wahoo. Hereafter, outputs y_1 , y_2 , and y_3 , are referred to as shallow water groupers, deep water groupers and non-reef fish, respectively.

Shallow water groupers make up 88.1% of the sample vessel catch, deep water groupers comprise 5.7%, and non-reef fish represent 5.0%. The two main variable inputs for reef fish vessels are labor, measured as the total number of captain plus crew days at sea, and fuel, which is measured as total gallons burned. The labor input is denoted x_1 and the fuel input as x_2 . Other variable inputs are ice used to preserve harvested fish, bait, and lost fishing gear. It is assumed that these inputs are used in proportion to the pounds of harvested fish. Ice, bait and lost gear costs are incorporated in the analysis below by adjusting the output price for fish.

Table 1 reports sample descriptive statistics. Notice that the composition of species harvested, and the scale of operation, measured by total catch and days at sea, varies widely across vessels. 149 vessels harvested shallow water groupers; 74 vessels harvested deep water groupers and 91 vessels harvested non-reef fish. The number of trips taken ranges from 1 to 77, and days at sea range between 1 and 256. Variation in vessel capital is also indicated; the average vessel length is 40.66 feet ranging between 20 and 73 feet.

⁸Harvested quantities within each output category are aggregated linearly. The aggregation procedure assumes that optimal input choices and aggregate output levels can be chosen independently of the mix of species within each output category. The harvest technology is thus assumed to exhibit weak output separability. Linear aggregation implies a constant rate of transformation among species within each output group.

⁹Discussion with fishermen indicated that shark species are harvested using similar methods and are found at similar depths as shallow water groupers. Sharks make up a small component (5.4%) of the first output category.

	Mean.	Std. dev.	Min..	Max.
Shallow water groupers (y_1)	27.01	29.97	0	133.62.
Deep water groupers (y_2)	1.67	6.20	0	61.79.
Non-reef fish (y_3)	0.34	0.96	0	6.98
Total Catch	29.02	30.39	0.13	133.75
Trips from Port	13.08	11.93	1	77
Days at Sea	63.58	53.86	1	256
Labor (x_1)	191.75	175.63	1	802
Fuel (x_2)	3,200.32	3,403.76	42	20,000
Vessel Length (feet)	40.66	10.80	20	73

Table 1: Descriptive Statistics for 1993 Reef Fish Vessels. Harvest quantities are thousands of pounds, labor is in units of worker days at sea, and fuel is in gallons. There are 150 observations.

4.1 First-stage estimation

An empirical estimate of the ODDF is obtained as the solution to the following linear programming problem

$$\begin{aligned}
(5) \quad & \vec{D}(x, y | g_y) = \max \beta \in \mathbb{R}_+ \\
& \text{s.t.} \quad (x, y + \beta g_y) \in \hat{T}(z),
\end{aligned}$$

where $y = (y_1, y_2, y_3)'$ is the output vector, $x = (x_1, x_2)'$ is the vector of variable inputs, and $\hat{T}(z)$ is an estimate of the feasible set, obtained as,

$$\begin{aligned}
(6) \quad & \hat{T}(z) = \{(x, y) : y_m + \beta g_{y,m} \leq \sum_{k \in \tilde{K}} \lambda_k y_{k,m}, \ m = 1, 2, 3, \\
& x_n \geq \sum_{k \in \tilde{K}} \lambda_k x_{k,n}, \quad n = 1, 2, \\
& \sum_{k \in \tilde{K}} \lambda_k = 1, \ \lambda_k \geq 0, \ k \in \tilde{K}\}
\end{aligned}$$

where m and n index outputs and variable inputs, respectively, λ_k is the intensity variable for vessel k , and \tilde{K} is the set of sample vessels from which the piecewise linear frontier is constructed (see Färe, Grosskopf, and Lovell, 1994, for details). For sample vessel k with length L_k , the set \tilde{K} is defined as sample vessels with length no greater than $L_k + 5$ feet,

	Mean	Median	Std. dev.	Min.	Max.
All vessels (150 boats)	0.53	0.47	0.29	0.05	1.00
Vertical line* (71 boats)	0.48	0.42	0.28	0.05	1.00
Long Line* (29 boats)	0.61	0.52	0.25	0.26	0.98
Fish trap* (20 boats)	0.52	0.40	0.37	0.14	1.00

Table 2: First-stage estimates of the output directional distance function. *- vessels harvesting with multiple gear types are excluded.

and no less than $L_k - 10$ feet. The feasible set is thus estimated from activity levels on vessels of similar size, i.e., vessels with presumably similar physical capital services. This approach is consistent with the assumption of local monotonicity in vessel capital services. The set of comparable vessels is assumed length-assymmetric, to capture the idea that the capital services provided by a smaller vessel should not exceed those provided by larger ones. In other words, the set of feasible variable inputs and outputs does not shrink when fishing takes place on a slightly smaller boat.

The constraint that intensity variables sum to unity is consistent with a variable returns to scale technology. The inequality constraint $\sum_k \lambda_k y_{k,m} \geq y_m + \beta g_{y,m}$ is consistent with strong output disposability. Alternative technological structures were tested and rejected. A Wilcoxon-Mann-Whitney test for constant returns to scale was rejected at the 91% level of confidence. A test of strong output disposability against the alternative of weak output disposability could not be rejected at conventional levels.

The ODDF is estimated for each vessel at directional vector $g_y = (y_{k,1}, y_{k,2}, y_{k,3})'$ for vessel k . Table 2 reports mean, median, standard deviation, minimum and maximum values of the first stage ODDF estimates for the full sample, and for each gear type.

4.2 Second-stage (stochastic frontier) analysis

Harvesting inefficiency—deviations from the piecewise linear frontier—can result from pure technical inefficiency, data errors, randomness in production, or the effects of un-measured inputs, such as unobserved variation in stock abundance, and/or un-measured physical and human capital. The second-stage analysis employs stochastic frontier methods to decompose

the first-stage ODDF estimate into technical inefficiency, the effects of un-measured inputs, and noise (data errors and random shocks).

Denote the first-stage ODDF estimate as $\widehat{\beta}_k$ for sample vessel k . $\widehat{\beta}_k$ can be expressed as the sum of pure technical (in)efficiency and noise,

$$(7) \quad \widehat{\beta} = u_k + v_k.$$

The first component, u_k , represents nonnegative pure technical inefficiency, and is assumed to be distributed as normally distributed random variable, with truncation from below at zero, variance σ_u^2 and variable mode $\alpha' z_k$. The vector z_k denotes exogenous environmental factors for vessel k and α is a vector of unknown parameters. The noise component $v_k \in (-\infty, \infty)$ is assumed to follow a normal distribution with zero mean and variance σ_v^2 . Noise may result from data errors and random harvesting shocks.¹⁰ If good and bad fishing luck is an important component of the noise term, the effects of luck will tend to *average out* as the amount of fishing increases. This implies a heteroskedastic specification for σ_v^2 . It is assumed that $\sigma_{v,k} = g(das_k, \gamma)$, where das_k is the days at sea for vessel k , and γ is an unknown parameter vector.

Assuming u_k and v_k are independent, the log likelihood for the k' th observation is given by (see Kumbhakar, and Lovell (2000)),

$$(8) \quad \begin{aligned} \ln L(\widehat{\beta}_k | z_k, das_k, \theta) = & -\ln \sqrt{2\pi} - \ln \sigma - \frac{(\widehat{\beta}_k - \alpha' z_k)^2}{2\sigma^2} \\ & + \ln \Phi\left(\frac{\alpha' z_k + \psi^2 \widehat{\beta}_k}{\sigma \psi}\right) - \ln \Phi\left(\frac{\alpha' z_i}{\sigma_u}\right), \end{aligned}$$

where, $\widehat{\beta}_k = u_k + v_k$, $\theta = (\alpha, \sigma_u, \sigma_v)$ is a vector of parameters, $\sigma^2 = \sigma_v^2 + \sigma_u^2$, $\psi = \sigma_u / \sigma_v$,

and Φ is the standard normal cumulative distribution function. The heteroskedastic noise is specified as $\sigma_{v,k} = \exp(\gamma_0 + \gamma_1 \ln das_k)$, which ensures $\sigma_{v,k} > 0$.

¹⁰In actuality, $D(x, y | g_x, g_y) \geq 0$ and thus v must lie in the interval $(-D(x, y | g_x, g_y), \infty]$. This restriction could be imposed by assuming v follows a bounded distribution, for example, a truncated normal. Analysis using this approach is reserved for future work.

Elements of z_k include vessel length, engine horsepower, and a proxy for the human capital endowed to the captain and crew, taken to be the vessel captain’s years of experience fishing for reef fish. Measures of stock abundance are unavailable. The data include the region of each vessels’ principle port. Regions range from 18 in the Florida Keys, to 24 in the northern waters of the fishery off of Franklin, Wakulla and Taylor counties which are located in northwest Florida. The region variable is used to control for possible (regional) differences in stock abundance.¹¹

4.3 Results

All variables are normalized by the respective means. Maximum likelihood estimation is carried out using Gauss. The model was estimated initially with elements of z entered linearly and quadratically, with and without a logarithmic transformation. It was determined that the linear-in-logarithmic form, with quadratic regional effects fit the data well, while providing a parsimonious model. Parameter estimates for the final model specification, along with 95% bootstrap confidence intervals are reported in Table 3. The bootstrap procedure is from Simar and Wilson (2003) and is described in an appendix.

Overall the results conform to expectations. Notice first that significant heteroskedasticity is indicated, with the variance of the symmetric noise found to be a declining function of vessel days at sea; γ_1 , is negative and statistically significant different from zero at the 95% level of confidence. Assuming good and bad luck in locating fish is an important feature of commercial fishing, the statistical model appropriately places more (less) weight on vessel observations that spend more (fewer) days at sea. Controlling for heteroskedasticity should thus provide a more robust characterization of the performance of a sustainable fishing operation.

The parameter associated with the linear Region variable is negative whereas the parameter associated with the quadratic Region variable is positive. Both are significantly

¹¹Measures of stock abundance aggregate information across time and space, are oftentimes constructed with the very productivity measures that are the focus of investigation, i.e., catch per unit effort data from commercial fisheries, and are usually accompanied by large confidence intervals. Regional effects implicitly treat reef fish stocks as a latent variable.

Variable	Parameter	Estimate	95% bootstrap c.i.
Intercept	α_0	0.881	[0.526, 1.160]
Region	α_1	-2.264	[-4.595, -0.111]
Region ²	α_2	25.046	[1.186, 54.832]
Ln(Exper.)	α_3	-0.352	[-0.722, -0.057]
Ln(length)	α_4	-2.332	[-3.797, -1.353]
Ln(engine h.p.)	α_5	0.489	[0.108, 1.015]
Asymmetric var.	σ_u	0.022	[1.516e-5, 0.152]
Intercept (σ_v)	γ_0	0.071	[-0.117, 0.172]
Ln(das)	γ_1	-0.422	[-0.535, -0.331]

Table 3: Stochastic frontier parameter estimates. ‘Region’ is region of vessel’s main port; ‘Exper.’ is years of captain experience reef fish fishing; ‘length’ is vessel length in feet; ‘engine h.p.’ is horsepower of main engine; ‘das’ is days at sea. The log likelihood function value is -259.095. There are 150 observations.

different from zero at the 95% level of confidence. Simple calculations reveal that vessels originating from ports in region 23.89 attain on average the lowest ODDF value. Region 23.89 falls between the 28 and 29 degree north parallel, which is slightly north of Tampa, Florida (Hernando, Citrus and Levy counties). Vessels originating from ports in this general vicinity tend to be more productive than vessels originating from ports located further south and further north.

Captain experience is found to have a negative and significant effect on the ODDF. This finding is as expected. Experience provides valuable knowledge about the location of reef fish across time and space and is found to increase output-oriented efficiency.¹²

Both measures of physical capital have statistically significant effects on harvesting efficiency. On average, larger vessels attain a lower ODDF.¹³ The results indicate that, all else equal, more engine horse power raises the value of the ODDF, and thus reduces output-oriented efficiency. This result is not surprising since large engines will on average

¹²Reef fish vessel captains keep detailed records of the times and locations that fish are caught, and an albeit thin market for record books exists in the reef fish fishery (Bob Spaeth, personal communication 2003).

¹³One explanation for this finding is the presence of part-time fishermen in the sample. The data indicate that 24% of the sample vessel operators earn part of their annual income in non-fishing activities. The average length of vessel’s operated by part-timers is 8 feet less than the length of full time boats. It is conceivable that part-time vessel captains are less concerned with productivity than full-time captains.

burn more fuel than smaller engines. A vessel that is *over-powered* relative to similarly sized boats may not harvest significantly more fish, but will utilize more fuel.

Summarizing the results in Table 3, heteroskedastic noise is indicated with noise variance found to be a declining function of days at sea. Stock effects, as measured by regional fixed effects, human capital and physical capital all have important effects on output-oriented harvesting efficiency. Larger, appropriately powered vessels that fish from ports located between the 28'th and 29'th north parallel and are operated by experienced captains tend to be most productive.

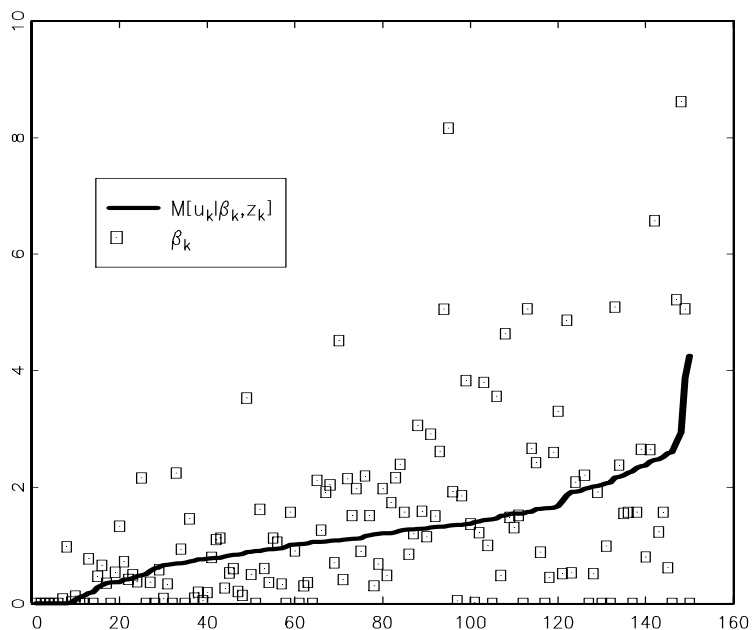


Figure 1: Estimates of modal output directional distance function

The effects of exogenous environmental factors on productivity of can be quantified by calculating the expected or *noise-free* ODDF for each vessel. Given the assumptions for the

composed error, the conditional mode of the ODDF for vessel k is given as

$$(9) \quad M[u_k|\beta_k, z_k] = \frac{\sigma_{v,k}^2 \alpha' z_k + \sigma_u^2 \beta_k}{\sigma_{v,k}^2 + \sigma_u^2}.$$

An estimate of the conditional mode is obtained by replacing the parameters in equation (9) with their estimated counterparts from Table 3. The results, along with the first-stage estimate, $\hat{\beta}_k$, are reported in Figure 1.

Further insights into the determinants of harvesting performance are obtained by calculating the effects of changes in z on the modal estimate of the ODDF, $M[u_k|\beta_k, z_k]$. To ease interpretation, these results are reported in terms of the Shephard output-oriented distance function, given by $(1 + M[u_k|\beta_k, z_k])^{-1}$.

The sample average of the Shephard output distance function is 0.51, with standard deviation 0.19, i.e., the sample boats harvested on average 51% of the frontier quantity of fish in 1993. This performance measure is conditional on z_k for $k = 1, \dots, K$. The effects of adjustments to capital and fishing location can be calculated directly. For instance, holding physical and human capital fixed, if all boats fished from ports located in the most productive region, region 23.89, the sample average value of the Shephard output distance function increases from 0.51 to 0.58 (standard deviation 0.20). This represents a 13.7% radial increase toward the harvest frontier, and can be interpreted as a 13.7% increase in catch.

Suppose next that all vessels fished from their respective port, with their respective physical capital, but that captains were endowed with more experience. A one standard deviation increase in experience, equal to 11.75 years, raises the sample average Shephard distance function to 0.56 with standard deviation 0.20; a 9.8% increase in output-oriented efficiency. If, all else equal, sample vessels harvested from an appropriately powered boat¹⁴, the sample mean value of the Shephard output distance function increases to 0.62 (standard deviation 0.22), representing a 21.6% increase in output efficiency. Finally, if all vessels

¹⁴ An appropriately powered boat is identified from the data. Each vessel k is assumed to have the lowest observed horse power for vessels in its length class $k \in \tilde{K}$, where \tilde{K} is defined following equation (5).

were 65 feet in length powered by a 300 horse power engine the sample average value of the Shephard output distance function increases to 0.98 (standard deviation 0.10).

These results suggest that stock effects have relatively small impacts on harvesting performance. This is not surprising. On the contrary, a finding of large differences in performance across regions would suggest a disequilibrium spatial distribution of the reef fish fleet. Reef fish vessels are mobile and can be expected to seek out lucrative stock concentrations. In equilibrium, all sites or regions should be equally productive. The small effects found in the data may represent a short run phenomenon, which is expected to dissipate over time as harvesting effort is redistributed toward the more productive north central region of the fishery.

Human capital effects are found to be relatively minor. Physical capital, in particular vessel size, on the other hand is an important determinant of harvesting efficiency.

The results are used next to test for differences in efficiency across gear types.¹⁵ Mean values of the Shephard output distance function for the three gear types are: 0.58 for the 29 vessels fishing with longline gear; 0.51 for the 71 vessel fishing with vertical hook and line gear, and 0.47 for the 20 vessel fishing with traps. A test of the null hypothesis of common efficiency for long line and vertical line boats is rejected at the 96.4% level of confidence. A test of the null hypothesis of common efficiency for long line and trap boats is rejected at the 99.4% level of confidence, whereas a test for common efficiency for vertical line and trap boats cannot be rejected at conventional confidence levels.

In sum, the results find that larger, appropriately powered vessels outperform smaller, and/or over-powered boats. Experienced captains are more productive than less experienced captains, and longline gear outperforms vertical line and fish trap gear.

Efficient vessel operations can earn higher profits per unit of harvest, and can profitably bid harvest permits away from than their less efficient counterparts. The results of this section provide some indication of the changes that might arise in a switch to rights-based management. To confirm these findings, fixed operating costs, which are expected to vary

¹⁵Vessels that used multiple gear types during 1993 are excluded.

across vessel of different lengths, must be examined. Fixed operating costs are presented in section 4.5. The results do not provide an indication of the *extent* of fleet restructuring that can be expected. Industry and managers are interested in knowing the number of inefficient boats that might exit under rights-based management.¹⁶ The next section presents measures of excess capacity to address this question.

4.4 Short run capacity

Excess harvesting capacity will be measured by comparing observed variable inputs and harvested output with capacity inputs and outputs. This comparative analysis will hold constant the output-oriented efficiency for each vessel. The goal is to hold constant the intrinsic performance of sample vessels, which is conditional on z_k , but control for and remove effects of noise in the data.

With this goal in mind, let $\partial y(x)$ denote the frontier catch attainable with variable inputs x . This catch is given as $\partial y(x) = \{y : \vec{D}(x, y|g_y) = 0\}$, and can be expressed as $\partial y(x) = y + \vec{D}(x, y|g_y)g_y$. Hence, with some simple manipulation

$$(10) \quad y = \left[\frac{\partial y(x)}{1 + \vec{D}(x, y|g_y)} \right] = D_o(x, y) \cdot \partial y(x),$$

where $g_y = y$. Notice in the above expression that as $\vec{D}(x, y|g_y)$ tends to zero, or equivalently as $D_o(x, y)$ tends to unity, the distance between output y and the frontier output $\partial y(x)$ tends to zero. The term $(1 + \vec{D}(x, y|g_y))^{-1}$ is a radial measure of distance to the frontier. The capacity measures that follow assume that vessel maintain a constant radial distance to the frontier as measured by $(1 + M[u_k|\beta_k, z_k])^{-1}$. For example, if the observed input allocation for vessel k is x_k , an estimate of the short run (noise-free) profit maximizing

¹⁶The *optimal* fleet structure in a fishery will depend on sustainable catch levels and prices, both of which are likely to be uncertain, and capital adjustment costs, among other factors. Kirkley, Morrison Paul and Squires (2002) provide further discussion of capacity utilization and its measurement in ocean fisheries.

catch is given as

$$(11) \quad \begin{aligned} y^*(x_k, z_k) &= \arg \max_{y \geq 0} \{py - wx_k\} \\ \text{s.t.} \quad y &\leq \frac{\partial y(x_k)}{1 + M[u_k|\beta_k, z_k]}. \end{aligned}$$

The output vector $y^*(x_k, z_k)$ maximizes variable profits subject to the constraint that the radially-adjusted output is contained in the producible set. As required $y^*(x_k, z_k)$ keeps constant the intrinsic efficiency of the vessel. (Dependence on z_k emphasizes the fact that this efficiency is conditional on exogenous environmental factors, z_k .) An estimate of $y^*(x_k, z_k)$ is obtained as the solution to the following programming problem,

$$\max_y \{py - wx : y \leq \frac{\sum_{k \in \tilde{K}} \lambda_k y_k}{1 + M[u_k|\beta_k, z_k]}, \quad x = x_k, \quad \sum_{k \in \tilde{K}} \lambda_k = 1, \quad \lambda_k \geq 0, \quad k \in \tilde{K}\},$$

where \tilde{K} is defined as above (the set of vessels with similar length).

Next define $y(x^*, z_k)$ as

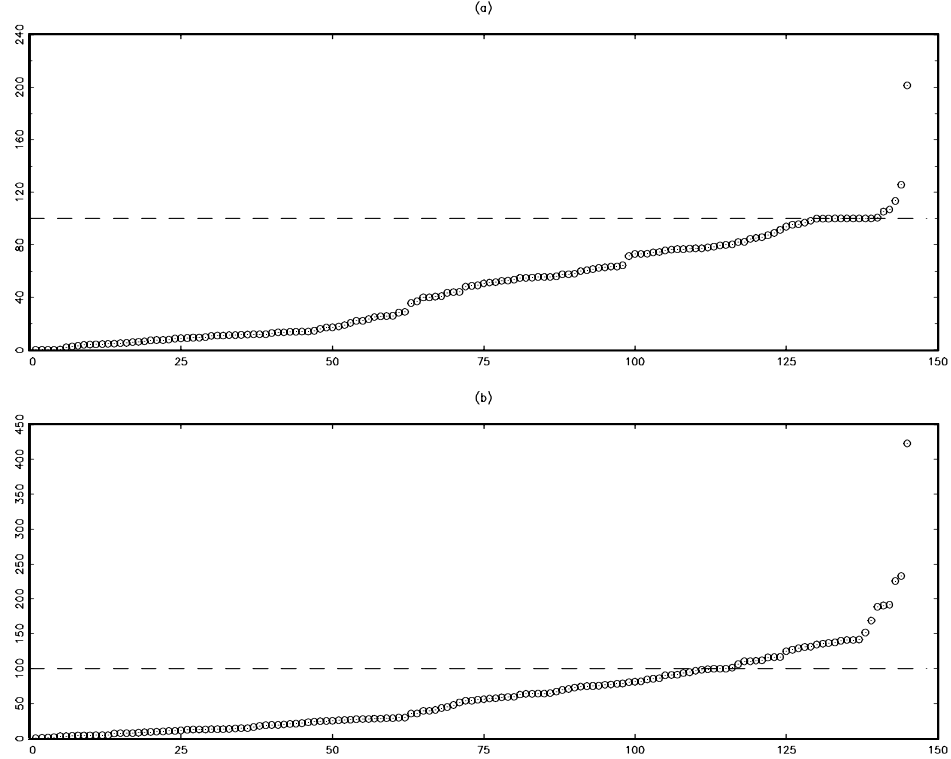
$$(12) \quad \begin{aligned} y(x^*, z_k) &= \arg \max_{y \geq 0} \{py - wx\} \\ \text{s.t.} \quad y &\leq \frac{\partial y(x^*)}{1 + M[u_k|\beta_k, z_k]}. \end{aligned}$$

The important difference in problem (12) is that the harvest quantity $y(x^*, z_k)$ assumes that vessel k employs the profit maximizing variable input bundle rather than the observed input x_k . Once again $y(x^*, z_k)$ maintains the radial distance to the frontier, given by $(1 + M[u_k|\beta_k, z_k])^{-1}$. An estimate of $y(x^*, z_k)$ is obtained as the solution to the following linear programming problem,

$$\max_{y, x} \{py - wx : y \leq \frac{\sum_{k \in \tilde{K}} \lambda_k y_k}{1 + M[u_k|\beta_k, z_k]}, \quad x \geq \sum_{k \in \tilde{K}} \lambda_k x_k, \quad \sum_{k \in \tilde{K}} \lambda_k = 1, \quad \lambda_k \geq 0, \quad k \in \tilde{K}\}.$$

The two output quantities, $y^*(x_k, z_k)$ and $y^*(x^*, z_k)$ are calculated for each sample vessel. Output and input prices are obtained from the cost survey data, yielding average prices,

$p_1 = \$1.98$ for shallow water groupers, $p_2 = \$1.92$ for deep water groupers and $p_3 = \$1.16$ for non reef fish. Output prices are adjusted downward by \$0.35 per pound to account for per-pound ice, bait and lost gear expenses. The average wage is $w_1 = \$150.03$ per crew labor day and the average price of fuel is $w_2 = \$0.88$ per gallon.



Short Run Capacity Utilization

To accommodate multiple outputs, panel (a) in Figure 2 reports the ratio of actual and capacity revenues, $p \cdot y^*(x_k, z_k) / p \cdot y^*(x^*, z_k)$, expressed in percentage terms.¹⁷ The revenue ratio measures range between 0.1% and 201.3% with most vessels (130 of 144) harvesting

¹⁷This measure is reported for 144 vessel observations for which feasible solutions for both $y^*(x_k, z_k)$ and $y^*(x^*, z_k)$ could be found. Common measures of capacity utilization, e.g., the ratio of observed and capacity output must be modified when multiple outputs are produced. An analysis of ray capacity utilization (see Segersen and Squires, 1993) produced similar results, but fewer feasible solutions.

less than the capacity revenue in 1993. Summing across vessel observations finds significant underutilization of available capital. The results find that 47.69% of the short run capacity revenue was attained in the 1993 by the 144 sample vessels depicted in Figure 2.

Panel (b) of Figure 2 reports the ratio of actual and capacity variable costs, $w \cdot x_k / w \cdot x^*$, where capacity variable inputs, x^* , yield from the solution to equation (12). The values range between 0.52% and 422.7% with most vessels (114 of 144 or 79.2%) employing less than capacity variable inputs. Summing across vessel observations finds that 49.4% of capacity variable costs were in employed by sample vessels in 1993.

Finally, subtracting variable costs from revenues finds that for the 144 vessels depicted in Figure 2, expected variable profits, which may be interpreted as the returns to the stock of physical, human capital and the reef fish stock, was \$3.690 million in 1993, which represents 39.8% of the capacity variable profits, estimated at \$9.265 million.

4.5 Fleet structure, harvest costs, permits prices, and resource rent under rights-based management

In this section, the model is used to predict the reef fish fleet structure, harvest costs, fishing permit prices and resources rents that are expected to emerge in equilibrium under property rights-based management. The analysis will consider representative vessel lengths ranging from 30 feet to 70 feet. Each representative vessel is assumed to fish from a port located in the average sample region, region 22.82. Captains of representative vessels are assumed to have average experience, 20.34 years, and each vessel is assumed to have the same engine horse power as sample vessels of similar length (estimated using ordinary least squares regression).

Reef fish vessels must make costly gear modifications to harvest non-reef fish, y_3 . These costs represent a superadditive fixed cost. No evidence is found to suggest cost complementarity between reef and non reef fish species, and thus the output mix under rights-based management is expected to consist primarily of shallow and deep water groupers, y_1 and y_2 . Predicting the precise mix of y_1 and y_2 under rights-based management will not be

Vessel length	y_1	y_2	Total catch	Variable cost	Fixed cost	RAC	Fleet Size
30	38.29	1.82	40.11	\$31.60	\$5.71	\$0.93	342
40	60.96	2.90	63.86	56.47	7.58	1.00	215
50	89.01	4.23	93.24	71.73	10.32	0.88	147
60	96.71	4.60	101.57	78.92	12.75	0.90	135
70	98.19	4.67	103.32	95.83	15.27	1.08	133

Table 4: Ray capacity output, harvest cost, and fleet size under rights-based management. Quantities are in thousands of pounds, total harvest costs are thousands of 1993 dollars, ray average costs are 1993 dollars.

attempted.¹⁸ To facilitate calculation of fleet sizes, the analysis assumes that the output mix for representative vessels is equal to the aggregate output mix harvested from the entire eastern Gulf reef fish fishery in 1993. National Marine Fisheries Service Log book data indicate that the total catch in 1993 consisted of 13.092 million pounds of shallow water groupers and 0.622 million pounds of deep water groupers, for a total of 13.754 million pounds of reef fish.¹⁹

Table 4 reports ray capacity harvest quantities, (only shallow and deep water grouper quantities are reported), total catch²⁰, variable cost (crew labor costs plus fuel expenses), fixed costs, ray average cost, and minimum fleet sizes for five representative vessel lengths. Fixed cost estimates are obtained from cost survey data and consist primarily of hull and gear maintenance costs, docking, licensing, administrative, and legal fees, and insurance costs. Ray average cost is calculated as variable plus fixed costs divided by total catch.

Minimum fleet sizes, reported in the last column of Table 4, are presented to illustrate the extent of fleet downsizing that may take place under rights-based management. The estimates are obtained by dividing the aggregate 1993 harvest of shallow and deep water groupers by ray capacity catch quantities, and can be interpreted as the minimum number of boats of a given length capable of harvesting the total 1993 reef fish catch. For example, if the fleet were made up entirely of 30 foot vessels each harvesting ray capacity output, 342

¹⁸See Squires and Kirkley (1995, 1996) and Weninger (1998) for additional discussion of equilibrium fleet structure in multi-species fisheries under rights-based management.

¹⁹The total catch of non-reef fish species was 0.651 million pounds in 1993.

²⁰The analysis permits positive quantities of y_3 to be harvested and thus total catch is greater than the sum of y_1 and y_2 for some vessel lengths, but only by a very small amount.

such vessels would be needed to harvest the 13.092 millions pounds taken from the fishery in 1993.

The results in Table 4 reflect the increased output-oriented efficiency on larger boats. RAC is lowest for a 50 foot boat but is only slightly higher on a 60 foot vessel. Interestingly, the results indicate that a 30 foot vessel attains comparable RAC at \$0.93 per pound to these larger boats. Note that RAC include variable costs plus fixed costs, and fixed costs are considerably less for smaller boats. The fixed cost advantage apparently offsets the inefficiency in variable operating profits that was found in the previous section. When fixed costs are considered, small boats are found to be economically competitive with larger boats.

Intermediate sized vessels, the 40 foot boat, and very large vessels, the 70 foot boat, attain higher RAC. Notice that the marginal increase in catch moving from a 60 foot to a 70 foot boat is small (2.05 thousand pounds). This is because the marginal efficiency gain on larger vessels is small, whereas variable and fixed costs continue to rise. The finding of high RAC on intermediate sized boats is less expected. One possible explanation is revealed from further examination of the data. Several smaller boats (< 35 feet in length) harvested large quantities of reef fish by taking many (often more than 50) short day trips. Large vessel harvesting large quantities took fewer but longer trips to sea. The strategy of taking short but frequent trips on a small boat may be an economically competitive one, since these vessel are relatively fuel efficient and incur smaller fixed operating costs.

Turning to predicted fleet sizes, the number of vessels required to harvest the 1993 catch ranges from 133 if the fleet were comprised entirely of 70 foot boats to 342 if the fleet is made up of 30 foot boats. Comparing these estimates with the actual reef fish fleet size in 1993 is difficult because *actual* fleet size is unknown. The National Marine Fisheries Service log book data indicates that 990 vessels harvested positive quantities of reef fish in the eastern Gulf in 1993. Many of these boats are part-time fishermen. However, of the 990 participants, 465 reported harvests in excess of 5,000 pounds, 331 reported harvests in excess of 10,000 pounds, and 229 reported harvests in excess of 20,000 pounds.

While a precise measure of actual fleet size in 1993 is unavailable, the results in Table

4 suggest significant fleet downsizing is likely under rights-based management. Total catch per vessel is predicted to be 40.11 thousand pounds for 30 foot boats and 103.32 thousand pounds for a 70 foot boat. From Table 1, the average catch of the 150 sample boats was a mere 29.02 thousand pounds.

The results find that differences in RAC for 30-60 foot vessels are not large. Assuming that the equilibrium rights-based fleet will be made up of 30-60 foot boats, the RAC is expected to average \$0.942 per pound. The total cost of harvesting the 1993 reef fish catch under this fleet structure is estimated at \$12.918 million. This cost estimate can be used to assess potential rent in the fishery under the rights-based program. Based on 1993 prices for reef fish, the rent (to the capital and fish stock) that is expected under the equilibrium fleet structure is \$0.71 per pound for shallow water groupers and \$0.65 per pound for deep water groupers. The total anticipated rent to the 1993 harvest of shallow and deep water groupers is estimated at \$9.662 million.

Finally, a comparison of potential and actual rent in the fishery provides an estimate of economic benefits of switching from the current management program to rights-based management. This calculation requires an estimate of the actual RAC incurred by the 1993 fleet. Calculating actual RAC for each sample vessel is straight forward. However, some sample vessels harvested non-trivial quantities of non-reef fish in 1993, and some participated in other fisheries. To obtain a representative estimate of actual RAC for reef fish only, sample vessels with a 90% or larger harvest share of reef fish (y_1 and y_2) are selected. For these vessels, a weight is calculated as $\phi_k = (y_{k,1} + y_{k,2}) / \sum_{k \in J} (y_{k,1} + y_{k,2})$, where J is the subset of vessels, 136 in all, with reef fish harvest share greater than 90%. The harvest share weighted RAC is then calculated as $\sum_{k \in J} \phi_k RAC_k^{actual}$. This calculation yields an estimate of actual RAC in 1993 equal to \$1.33 per pound, and an estimate of total fleet harvesting cost (for reef fish only) equal to \$18.186 million.

Comparing this cost estimate the cost predicted under the rights-based management finds that the 1993 reef fish catch could have been taken at 71.0% of the actual cost that was incurred. This translates to a predicted harvest cost saving of \$5.518 million under rights-based management.

5 Conclusion

This paper applies a two-step methodology to analyze harvesting efficiency and capacity utilization in the eastern Gulf of Mexico reef fish fishery. The empirical model directly accounts for the effects of data errors and random production shocks and is particularly well-suited for analyzing economic performance in commercial fisheries. Moreover, the approach can be used when only primal data are available and easily accommodates multiple inputs and multiple outputs.

The methodology is used to predict changes in vessel catch rates, fleet structure, harvesting costs and resource rents that are expected to emerge if the current controlled access management program in the eastern Gulf reef fish fishery is replaced with a property rights-based program. The results find that larger vessels, which are appropriately powered, outperform smaller and/or over powered boats. Experienced captains outperform their less experienced counterparts and long line gear is more productive than vertical hook and line or fish trap gear. These results suggest that a switch to rights-based management will result in a redistribution of catch to large longline vessels operated by experienced captains. The analysis also finds significant excess harvesting capacity in the 1993 data. Estimates suggest that the total reef fish catch in 1993 could have been harvested for \$5.518 million less than actual costs, if taken by the fleet structure that is expected to emerge under rights-based management. The estimated cost saving can be interpreted as the cost of maintaining the current command and control management program in the eastern Gulf reef fish fishery.

The estimated economic benefits represent potential rent gains under the fleet structure that is expected to emerge if rights-based management is adopted. However, significant fleet downsizing must occur before the benefits are realized. Delays in the transition to the smaller fleet can take time, and exiting boats could relocate to other fisheries causing further management problems. Designing and implementing a rights-based management program presents a serious challenge for regulators and industry. On the other hand, continuing with the current management approach based on input control does not hold much promise. Regulators are currently considering proposals to adopt per trip catch limits and further

restrict areas in which longline gear can be used.²¹ A proposal to ban fish trap gear by 2007 has already been adopted by the Gulf management council. These regulations may reduce reef fishing mortality but can only cause further increases in harvesting costs.

Rights-based management represents an attractive alternative to command and control. Based on the analysis of 1993 data, the economic gains under a rights-based approach are expected to be large.

²¹This paper finds that long line vessels are the most productive segment of the reef fish fleet. Restrictions on longline vessels may be attractive since they may also lead to relatively large reductions in fishing mortality.

6 References

- Chambers, Chung and Färe (1996), Benefit and Distance Functions, *Journal of Economic Theory* 70, 407-419.
- Dupont, D. (2000), Individual transferable vessel quotas and efficient restructuring of the primary harvesting sector, *Ann. Operations Res.* 94, 275-294.
- Dupont, D., R. Q. Grafton, J. Kirkley and D. Squires (2002), Capacity utilization and excess capacity in multi-product privatized fisheries, *Resource Energy Econ.* 24, 193-210.
- Färe, R., and S. Grosskopf (2000), Theory and Application of Directional Distance Functions, *Journal of Productivity Analysis*, 13, 93-103.
- Färe, R., S. Grosskopf and C. A. K. Lovell. *Production Frontiers*, Cambridge University Press, Cambridge, UK, 1994.
- Felthoven, R. G., Effects of the American Fisheries Act on capacity, utilization and technical efficiency (2002), *Marine Resource Economics* 17, 181-1205.
- Freid, H. O., C. A. K. Lovell, S. S. Schmidt and S. Yaisawarng (2002), Accounting for Environmental Effects and Statistical Noise in Data Envelopment Analysis, *Journal of Productivity Analysis* 17, 157-174.
- Grosskopf, S., Statistical inference and nonparametric efficiency: a selective survey (1996), *Journal of Productivity Analysis*, 7, 161-176.
- Gstach, D., Another approach to data envelopment analysis in noisy environments, DEA+ (1998), *Journal of Productivity Analysis*, 9, 161-176.
- Grafton, Q., D. Squires, and K. Fox (2000), Private property and economic efficiency: a study of a common-pool resource, *Journal of Law and Economics*, 63, 679-713.

Kirkley, J., C. J. Morrison Paul and D. Squires (2002), Capacity and capacity utilization in common pool resource industries, *Environmental and Resource Economics*, 22, 71-97.

Kirkley, J., D. Squires, and I. E. Strand (1995), Assessing technical efficiency in commercial fisheries: the mid-Atlantic sea scallop fishery, *American Journal of Agricultural Economics*, 77, 686-697.

Kumbhakar, S. C. , and C. A. K. Lovell, *Stochastic Frontier Analysis*, Cambridge University Press, 2000.

Marcoul, P., and Q. Weninger, Fishing for information, mimeo, Iowa State University, August, 2003.

Segerson, K. and D. Squires (1993), Capacity utilization under regulatory constraints, *The Review of Economics and Statistics*, 75, 76-85.

Shephard, R. W. (1970) *Theory of Cost and Production Functions*. Princeton: Princeton University Press.

Simar, L., and P. W. Wilson (2003) Estimation and inference in two-stage, semi parametric models of production processes, Discussion paper 0307, Institut De Statistique, Universite Catholique de Louvain.

Squires, D., M. Alauddin and J. Kirkley (1994), Individual transferable quota markets and investment decisions in the fixed gear sablefish industry, *Journal of Environmental Economics and Management*, 27, 185-204.

Squires, D., and J. Kirkley (1995), Resource rents from single and multispecies individual transferable quota programs, *ICES J. Marine Sci.* 52, 153-164.

Squires, D., and J. Kirkley (1996), Individual transferable quotas in a multiproduct common

property industry, *Canadian Journal of Economics*, 24, 318-342.

Smith, M. D. (2000), Spatial search and fishing location choice: methodological challenges of empirical modeling, *American Journal of Agricultural Economics*, 82, 1198-1206.

Waters, J. R. An Economic Survey of Commercial Reef Fish Vessels in the U.S. Gulf of Mexico. National Marine Fisheries Service, National Oceanic and Atmospheric Administration, unpublished report, July, 1996.

Weninger, Q. (1998), Assessing Efficiency Gains from Individual Transferable Quotas; An Application to the Mid-Atlantic Surf Clam and Ocean Quahog Fishery, *American Journal of Agricultural Economics*, 80, 750-764.

Weninger, Q. and I. E. Strand (2003), An empirical analysis of production distortions in the mid-Atlantic surf clam and ocean quahog fishery, *Applied Economics*, 35, 1191-1197.

Weninger, Q. and J. Waters (2003), Economic benefits of management reform in the northern Gulf of Mexico reef fish fishery, *Journal of Environmental Economics and Management*, 46, 207-230.

7 Appendix

Simar and Wilson 2003 present a bootstrap algorithm designed for the two-stage estimation procedure. This appendix describes the algorithm used to calculate confidence intervals reported in Table 3. The first stage data envelopment analysis and second stage maximum likelihood estimation yield, for each vessel observation k , parameter estimates $\hat{\beta}_k$, $\hat{\alpha}_k$, $\hat{\sigma}_u$, and $\hat{\sigma}_{v,k}$. These parameter estimates are used in the following algorithm. Note that the distributional assumptions for u_k are equivalent to assuming $u_k = \alpha'z_k + \eta_k$ where η_k is distributed as a mean zero, variance σ_u^2 , random variable that is truncated from below at $-\alpha'z_k$.

1. Using a standard transformation technique (see the appendix of Simar and Wilson, 2003) η_k^* is drawn from a mean zero normal distribution with variance $\hat{\sigma}_u^2$, and lower truncation point $\hat{\alpha}'z_k$. A second random term $v_k^* \sim N(0, \hat{\sigma}_{v,k})$ is drawn and added to obtain $\tilde{\beta}_k^* = \tilde{u}_k^* + \tilde{v}_k^*$, for $k = 1, \dots, K$.
2. Given the pseudo data $\{\tilde{\beta}_k^*\}$, maximum likelihood is used to estimate parameters $\hat{\alpha}_k^*$, $\hat{\sigma}_u^*$, and $\hat{\sigma}_{v,k}^*$.
3. Steps 1 and 2 are repeated J times, yielding the bootstrap sample $C = \{\hat{\alpha}_k^*, \hat{\sigma}_u^*, \hat{\sigma}_{v,k}^*\}_{j=1}^J$.

The procedure is implemented with $J = 500$. 95% confidence intervals are obtained by sorting the parameters in C from smallest to largest and identifying the lower 2.5 percentile value and the upper 97.5 percentile value. These values are reported in Table 3. Note that σ_u is restricted to be positive and thus the 2.5% value is positive by construction.